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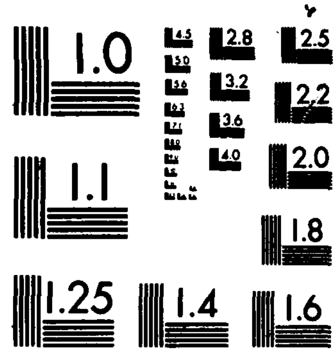

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Review of 183 GHz Moisture Profile Retrieval Studies

R.G. Isaacs

Atmospheric and Environmental Research, Inc.
840 Memorial Drive
Cambridge, MA 02139

15 April 1987

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A brief review of published studies of water vapor retrievals using the millimeter wave water vapor resonance at 183.31 GHz is presented. Both simulation and aircraft experimental studies are covered. Results are summarized based on meteorological, sensor system, and retrieval approach considerations. A number of problem areas are identified including those associated with uncertainties in millimeter wave optical properties of surfaces and gaseous absorption and the dielectric properties of liquid and solid water species, the potential effects of clouds and precipitation, and surface elevation effects.

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1. Introduction

The ability to measure, infer, or predict the spatial distribution of atmospheric water vapor is desirable to support a variety of meteorological applications models used by the Air Force (Moore and Peterson, 1984). Operational requirements for the collection of water vapor distribution data currently exist on a variety of spatial scales ranging from local to global domains (Aerospace, 1983). On synoptic scales, for example, water vapor distribution data support the analysis and forecasting of frontal system development, advection, and the extent of related air mass characteristics. Moisture availability also provides a measure of the energy available for latent heating. Water vapor is the precursor for a variety of liquid water species such as cloud, fog, and precipitation, each of which affects both the meteorological and operational environment. Cloud occurrence, for example, is a constraint on tactical operations such as close air support and precipitation history determines land trafficability. Vertical moisture profile information is desired to enable forecasting of cloud strata and vertical refractive index gradients. The abundance of water vapor also affects atmospheric transmission and propagation both directly through water vapor absorption and indirectly through relative humidity effects on the growth of ambient aerosol species (Kneizys et al., 1983; Shettle and Fenn, 1979). Transmission and electro-optical propagation degradation can impact a variety of communications, sensor, and surveillance systems.

The implications of improved capabilities to specify the global moisture field for numerical weather prediction applications is particularly promising (Isaacs et al., 1986). Radiatively, water in its many forms is the most active constituent of the troposphere. Clouds and water vapor profoundly affect the parameterization of radiative heating within the atmosphere (WMO, 1978). A variety of studies have shown that updating the moisture field can improve short range precipitation forecasts (Perkey, 1980; Maddox et al., 1981) and that latent heat released by condensation can have large short term influence on storm development (Anthes et al., 1983).

Conventional observations of the moisture distribution include surface observations, from airfields and other installations, of the moisture in the lowest few meters of the atmosphere and upper air data from radiosondes. These data are augmented with data buoys at sea, automated stations over land, and available aircraft reports. Considerable data voids exist, however, especially over the world's oceans and over the southern hemisphere. Furthermore, a considerable percentage of the existing conventional data is obtained from non-U.S. sources. In the event of hostilities, the potential exists for significant portions of this non-U.S. conventional data to be denied when it is operationally necessary. Satellite observations are an invaluable source of supplementary data both to fill existing data sparse regions and to substitute for conventional sources from data denied areas. Applications of remotely sensed data to fulfill Air Force requirements related to numerical weather prediction have recently been reviewed (Kaplan et al., 1983). The moisture sounders to satisfy Air Force operational requirements, however, are severely limited.

Existing satellite borne moisture sounders are infrared instruments such as the HIRS-2 component of the polar orbiting TIROS-N Operational Vertical Sounder (TOVS) (Smith et al., 1979) and the VISSR Atmospheric Sounder (VAS) aboard the geosynchronous GOES series (Smith et al., 1981). These instruments have exploited the infrared rotation-vibration bands near 6.7 μm. A DMSP infrared sensor designed to obtain temperature and moisture profiles, the SSH-2, used seven channels in the 20 μm infrared water vapor rotational band (see Valovcin, 1981). In general, the accuracy of the water vapor retrievals from these instruments has not been regarded as sufficient to use them operationally for numerical weather prediction purposes. Goals for TOVS moisture retrievals, for example, are limited to precipitable water values in three broad vertical layers at accuracies of +/-30% (NOAA,1981).

The presence of clouds within the field of view is a particular problem inherent to infrared instruments. Clouds, particularly liquid water clouds, are optically thick at infrared wavelengths. Therefore, atmospheric emission from levels below cloud top does not contribute to sensor incident radiances and retrievals of temperature and moisture are precluded below cloud top level. Additionally, the sensitivity of infrared radiances to variations in the abundance of water vapor near the earth's surface is quite weak (Rosenberg et al., 1983). This is due to a trade-off between emission from water vapor near the surface and the transmission of surface emission. An increase of water vapor abundance near the surface enhances atmospheric emission and reduces the surface contribution. A decrease of water vapor near the surface has the opposite effect. When the ambient atmospheric temperature near the surface is close to the surface temperature (as it often is) and surface emissivity is near unity (as it is in the infrared region), these effects tend to cancel one another.

Satellite borne microwave instruments offer distinct advantages over their infrared counterparts, particularly as regards the effects of clouds and surface emissivity. At the longer wavelengths associated with microwaves (two to three orders of magnitude greater than in the infrared), most liquid water clouds are optically thin and ice clouds are virtually transparent. At half centimeter wavelengths (i.e. 60 GHz) used for temperature profiling by the SSM/T-1, for example, clouds appear to have little effect (Staelin et al., 1975; Liou et al., 1981; Grody et al., 1984). Furthermore, many terrestrial surfaces (most notably, the calm ocean surface) have emissivities substantially less than unity at these wavelengths. For this reason water vapor emission over the ocean can be sensed in contrast to the radiometrically cold, nonblackbody surface emission (Staelin et al., 1976; Alishouse, 1983). It would be quite desirable to extend these advantages to the profiling of water vapor.

Microwave water vapor remote sensing has used the weak rotational line at 22.235 GHz (1.35 cm) to obtain precipitable water over the oceans (Staelin et al., 1976). Unfortunately, this feature has a total zenith opacity of only 0.5 dB for 1.5 cm of precipitable water (Smith and Waters, 1981) and cannot support a reliable water vapor profile. The next rotational line (3_{13}- 2_{20}) is in the millimeter wave region at 183.31 GHz (0.164 cm). This feature is about two orders of magnitude stronger and can support a water vapor sounding capability (Schaerer and Wilheit, 1979). A number of investigators have discussed the use of this feature both in simulation studies (Rosenkranz et al., 1982; Kakar, 1983; Kakar and Lambrigtsen, 1984; Isaacs et al., 1985a, 1985b) and based on radiometer data obtained from aircraft (Wang et al., 1983). These studies have been conducted in support of 183 GHz radiometers designed for both the next generation civilian sounding package, the Advanced

Microwave Sounding Unit (AMSU) B package (Schutz, 1982; NOAA, 1983) and a water vapor sounding enhancement to the DMSP microwave temperature sounder, the SSM/T-2 (A. Stogryn, personal communication).

This report will review, evaluate, and summarize current research and results on the estimates of the accuracy of water vapor/relative humidity profiles obtained from 183 GHz radiometers.

2. Review of Moisture Profile Retrieval Studies

A handful of published papers and technical reports are currently available which discuss the retrieval of water vapor profiles from observations (either simulated or collected by aircraft-borne radiometers) of atmospheric brightness temperatures in the vicinity of the 183.31 GHz water vapor line. In this section we review the results of work performed by five groups: ERT, NASA, MIT, JPL, and AER. Results of simulation studies performed by Aerojet are included in Appendix A. They were available only as viewgraphs. The studies summarized in this review are listed in Table 2-1.

Table 2-1 Listing of papers and technical reports treating water vapor profile retrieval employing 183 GHz data.

Investigators / Date	Organization	Approach	Reference
Gaut et al. 1975	ERT, Inc.	Use of 183 GHz and other channels for water vapor and cloud properties	AFGL-TR-75-0007
Schaerer and Wilheit, 1979	NASA	Profile retrieval simulation using 5 channels and iterative method	Radio Science, 14, 3, 371-375.
Rosenkranz et al. 1982	MIT	Statistical retrieval based on 60 GHz and 183 GHz simulations	J. Appl. Meteor. 21, 1364-1370.
Wang et al. 1983	NASA	Aircraft radiometer data and retrieval	J. Clim. and Appl. Meteor., 22, 779-788.
Kakar 1983	JPL	Chahine-type retrieval	J. Clim. and Appl. Meteor., 22, 1282-1289
Kakar and Lambrigsten, 1984	JPL	Statistical correlation technique	J. Clim. and Appl. Meteor., 23, 1110-1114.
Isaacs and Deblonde 1985,1987	AER	Statistical retrieval,	AFGL-TR-85-0040; AFGL-TR-85-0095. Radio Science, 22 3,367-377.

2.1 Gaut et al., 1975

The primary focus of this study was the potential effect of clouds and precipitation on microwave temperature retrieval accuracy. However in the course of this investigation, techniques were also examined to obtain cloud properties using data from microwave radiometers. To place this study in perspective, this work followed a series of studies performed by ERT in the early seventies supported by the Air Force directly and as a subcontractor to Aerojet Electro-Systems Company which sought to define candidate microwave remote sensing systems to satisfy Air Force meteorological data requirements.

A variety of candidate systems were defined and their capabilities explored through simulation and retrieval exercises. Some of the parameters investigated included: (a) total integrated water vapor, (b) the vertical distribution of water vapor, (c) temperature profile, and (d) the integrated and vertical distribution of cloud liquid water.

Although most emphasis was placed on channels selected below 60 GHz, some work was done to evaluate the impact of higher frequency channels including those in the vicinity of 183 GHz. The rationale for selecting higher frequency channels was threefold. First, it was desired to mitigate the effect of variable surface emissivity over land at lower frequencies which were used to obtain water vapor information. These channels in the vicinity of the 22.235 GHz water vapor line can often see the surface, i.e. the atmosphere is optically transparent. Thus, the spatial variation of the background emission is difficult to separate from the variation of atmospheric water vapor emission contributing to the total observed brightness temperature. By selecting channels in the vicinity of an intense water vapor feature such as the line at 183.31 GHz, it was proposed that the effects of variable surface emission could be masked. Even so it was realized that obtaining information for the layers nearest to the surface would be difficult.

Secondly, it was postulated that higher frequency channels could be exploited to provide information on cloud vertical structure. Infrared data provide information on cloud tops but do not differentiate between water and ice clouds. At higher frequencies, brightness temperatures are sensitive to water clouds but relatively insensitive to ice clouds. Therefore, combination of infrared and microwave channels could potentially yield information on the type of cloud and vertical structure within the field of view. It was also proposed that channels with similar weighting functions from the 60 GHz oxygen complex and 118 GHz oxygen resonance could be combined to provide information on the vertical structure of clouds. These paired channels would provide redundant information in clear situations. In cloudy situations, however, brightness temperatures would differ since cloud emission increased at the higher frequencies. Finally, higher frequency channels would be more sensitive to the integrated water vapor of clouds with relatively small liquid water content.

Gaut et al., performed a preliminary study to examine the effect of high frequency channels on the retrieval of cloud liquid water profiles. Three layers were defined corresponding to low (0 to 3 km), middle (3-6 km), and high (6-20 km) clouds. Integrated water vapor and layer integrated cloud liquid water was retrieved from a variety of channel sets in the oxygen bands (i.e. temperature retrieval bands), a channel at 22 GHz, and various higher frequency channels: one at 183 GHz and a set including channels at 94, 140, and 170 GHz. Retrievals were performed using a statistical "D" matrix type algorithm and a midlatitude summer atmospheric sounding set. Table 2-2 summarizes their results. The figure of merit is the ratio of the a priori standard deviation of each parameter to that obtained by the retrieval, i.e. the higher the figure of merit, the better the retrieval. It can be seen that temperature channels alone provide some marginal skill in retrieving both integrated water vapor and layer cloud liquid water amounts. Gaut et al., attribute this to the effects of the 183 GHz line extending into the 118 GHz region. However, inclusion of the channel at 22 GHz is critical to the accuracy of these retrievals, especially for integrated water vapor. For integrated water vapor, the 183 GHz channel provides very little information above that given by the 22 GHz channel. However, for the cloud liquid water retrieval, the 183 GHz channel does almost as well alone as the 22 GHz channel does alone. Combined, these two additional channels (i.e. 22 and 183 GHz) markedly improve the cloud liquid water retrieval in the lowest layer.

Table 2-2 Integrated water vapor and cloud liquid water retrieval results using 183 GHz data (from Gaut et al., 1975)

	Figure of Merit Channel Set			
Parameter	Set A	A+22	A+183	A+22+183
Integrated Water Vapor	2.18	21.08	2.85	23.42
Liquid Water (0-3 km)	1.74	2.89	2.68	3.69
Liquid Water (3-6 km)	1.28	1.40	1.34	1.48
Liquid Water (6-20 km)	1.38	1.55	1.50	1.58

Set A: 53.29 GHz 117.76 GHz
54.30 118.00
55.46 118.22
58.80 118.50
59.50 118.675

Calculations were also performed to investigate cloud type discrimination and cloud top altitude determination using 140, 170, and 183 GHz data in conjunction with an infrared window channel. For the case of a liquid water cloud, it was demonstrated that the brightness temperature at 170 GHz was very close to that of the physical temperature of the cloud top. For the case of an ice cloud over a liquid water cloud, it was demonstrated that the brightness temperature at 170 GHz was close to that of the top of the liquid water cloud, while the infrared brightness temperature was close to that near the top of the ice cloud. (The calculation assumed that the ice cloud was opaque in the infrared which might not be true, and that the ice cloud was transparent at 170 GHz which may also be questionable.) Thus, it was suggested that such channel combinations could be used to differentiate between ice and liquid water clouds, and in conjunction with temperature profile data, to obtain information an the cloud vertical extent.

It is interesting to note that this study focused almost exclusively on the use of higher frequency millimeter wave channels for the retrieval of cloud properties, rather than on their application to the water vapor profile retrieval problem.

2.2. Schaerer and Wilheit, 1979

These investigators made a preliminary analysis of the feasibility of profiling water vapor using simulated 183 GHz brightness temperature data. The inherent differences between temperature and constituent retrievals were discussed from the perspective of the 183 GHz water vapor retrieval problem. The radiative transfer equation was linearized to examine the effect of an increase in relative humidity on brightness temperature through changes in the water vapor absorption coefficient, γ. These changes were related by:

$$\Delta T_{b\uparrow} = \int_0^\infty G_R(h)\Delta R(h)dh \qquad (2.1)$$

where R(h) is the profile of relative humidity, $\rho(h)$ is the water vapor pressure, and the weighting function $G_R(h)$ was defined as:

$$G_R(h) = G(h)\,\frac{\partial\gamma(h)}{\partial\rho(h)}\,\frac{\partial\rho(h)}{\partial R(h)} = G(h)\,\frac{\partial\gamma(h)}{\partial\rho(h)}\,\rho_{SAT}(h) \qquad (2.2)$$

where

$$\begin{aligned} G(h,\ \gamma(h),\ T(h)) = {} & e^{-\tau(h\infty)}\left[T(h) - T_{\beta\uparrow}(h)\right] \\ & + Re^{-\tau(0,\infty)}e^{-\tau(0,k)}\left[T(h) - T_{\beta\downarrow}(h)\right] \end{aligned} \qquad (2.3)$$

Figures 2-1 and 2-2 from Schaerer and Wilheit (1979) show these weighting functions calculated at 2, 4, 6, 10, and 18 GHz below the 183 GHz line for tropical ocean over the ocean and land, respectively. The authors note that as one moves away from the line center (see Figure 2-1), the weighting function probes deeper into the atmosphere, i.e. to lower altitudes. Notably, at lower altitudes the weighting functions actually change sign. Thus, an addition of water vapor at these levels will increase the observed brightness temperature (see Equation 2.1) rather than decrease it as is usually the case. Over land (Figure 2-2), this crossover occurs at lower altitudes, if at all. For blackbody surface emission, the sign change does not occur. This sign change does not exist at all for temperature weighting functions.

A retrieval scheme based on iterating from an initial guess was investigated. A synthetic data set was calculated for five channels at frequencies of 183.3, 182.0, 180.0, 174.0, and 140.1 GHz. Using the initial guess profiles (the temperature profile was assumed known), brightness temperatures and weighting functions were calculated. The differences between the calculated brightness temperatures and those of the synthetic data set were used to adjust the relative humidity profiles using the weighting functions. Adjustments were performed at the weighting function peaks and piecewise linear profiles were constructed. This process was iterated until brightness temperature residuals were within 1 K. The retrieval was successful for smooth profiles such as that of the U.S. Standard atmosphere. Properties such as the boundary layer structure associated with the trade inversion in the tropical atmosphere could not be resolved. It was concluded that microwave radiometry near the 183 GHz line could provide useful water vapor profile retrievals, at least over the oceans.

2.3 Rosenkranz et al., 1982

Significantly, Rosenkranz et al., suggested that the channels from the 183 GHz water vapor absorption region should be augmented with those from the oxygen complex in the vicinity of 60 GHz. The water vapor profile retrieval is then accomplished by combining retrievals obtained from each spectral region using a simple linear estimation algorithm. This statistical approach is analogous to that used by Gaut et al. (1975) and differs considerably from that applied by Schaerer and Wilheit (1979). The authors prefer the approach because of its robustness and simplicity. Since it is a linear approach and the relationship between water vapor abundance and brightness temperature is not linear, the profile information is obtained by retrieving water vapor burden profiles. Water vapor burden is defined as the column integrated water vapor above a given pressure level. An estimate of the desired parameter vector, p, (i.e. either water vapor burden or atmospheric temperature) is obtained from the data vector, d, of observed brightness temperatures using:

$$p - \langle p \rangle = R_{pd} R_{dd}^{-1} (d - \langle d \rangle) \qquad (2.4)$$

where the angle brackets denote ensemble means and the R_{pd} and R_{dd} are the covariance matrices of the data and parameter vectors and that of the data with itself. These statistics are derived from a priori ensembles of parameter vectors and actual or simulated data.

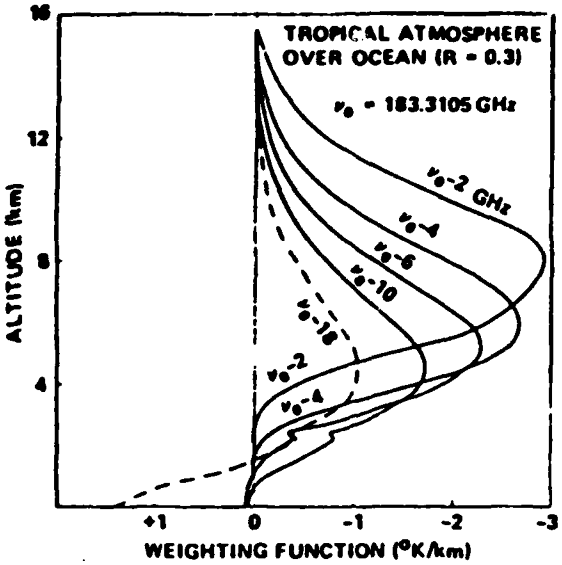

Figure 2-1 Relative humidity weighting functions for Tropical atmosphere over the ocean (Schaerer and Wilheit,1979).

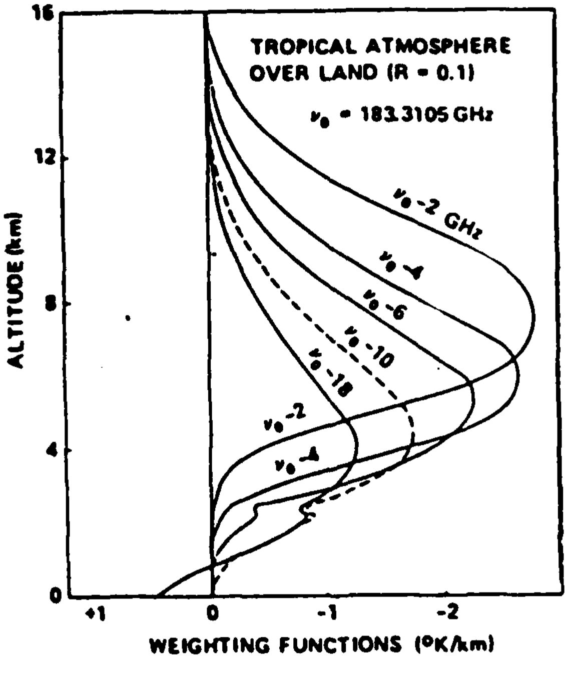

Figure 2-2 Relative humidity weighting functions for Tropical atmosphere over land (Schaerer and Wilheit,1979).

The method relies on using the 183 GHz and 60 GHz spectral regions as sources of data for the inference of two atmospheric temperature profiles: (a) that of temperature vs. pressure (i.e. the temperature profile) and (b) that of temperature vs. water vapor burden. Combination of these two profiles results in the water vapor burden vs. pressure which can then be expressed as a layer water vapor abundance profile. The temperature profile is, of course, also obtained. The method is illustrated graphically in Figure 2-3 from Rosenkranz et al. The preliminary water vapor burden profile obtained as described above can be used together with the water vapor brightness temperatures in another step of regression (Equation 2.4 above) to obtain a more refined profile. Using this approach, RMS errors in relative humidity (obtained from the burden profiles) were improved 20-24% compared to those obtained with straight linear regression techniques.

For cases over the oceans, Rosenkranz et al., supplemented the 60 and 183 GHz data with lower frequency channels at 18.5, 22.23, and 31.65 GHz. Figure 2-4 illustrates water vapor burden retrieval errors obtained with this channel set. Analogous results for relative humidity are shown in Figure 2-5.

These investigators suggest that comparison of the retrieved water vapor burden with the curve of saturated water vapor burden obtainable from the corresponding retrieved temperature profile, can provide a way of detecting the presence of an opaque cloud. Furthermore, they note that semitransparent cloud and cloud which does not fill the field of view may require other approaches. They do not however, treat cloud in their retrieval approach.

2.4 Wang et al., 1983

This study reports on the results of water vapor profile retrievals obtained from an aircraft-borne 183 GHz radiometer flown during the 1981 Cooperative Convective Precipitation Experiment (CCOPE). The instrument used four double sideband channels at 91.65, 183.3+/-2, 183.3+/-5, and 183.3+/-9 GHz. The retrieval technique was based on a modified Kalman-Bucy filter technique such as that applied by Ledsham and Staelin (1978) to the temperature retrieval problem. The modification for the water vapor retrieval problem was necessary to account for the variation of the weighting functions with the temporal and spatial variation of the water vapor itself.

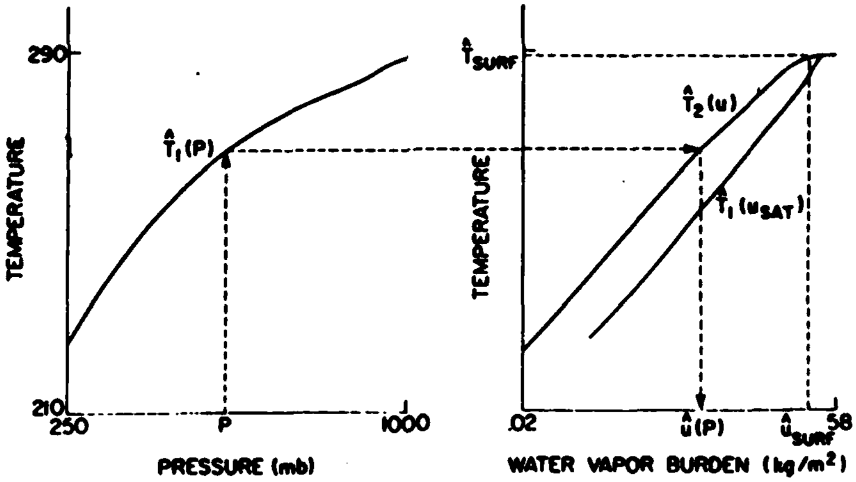

Figure 2-3 The method of obtaining water vapor burden, u, as a function of pressure, p, given two estimated temperature profiles. (From Rosenkranz et al., 1982.)

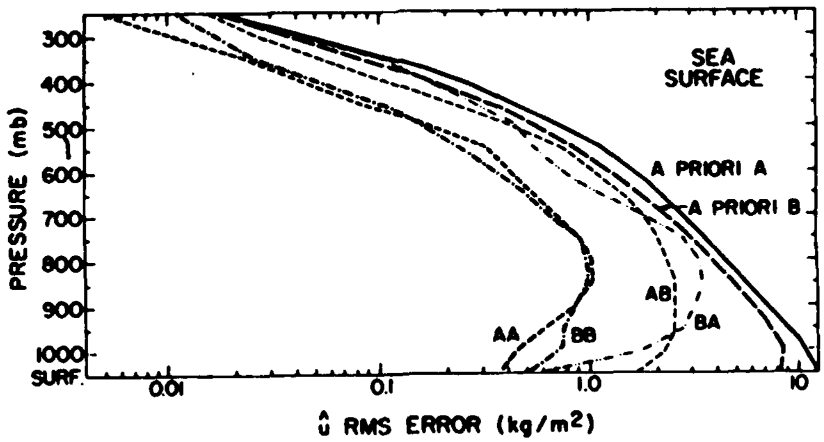

Figure 2-4 Residual errors in estimated water vapor burden over a smooth ocean surface. A priori A and B are variance of of the sets used. Other curves such as AB, etc. denote retrievals from B set simulated data using A set statistics, etc.

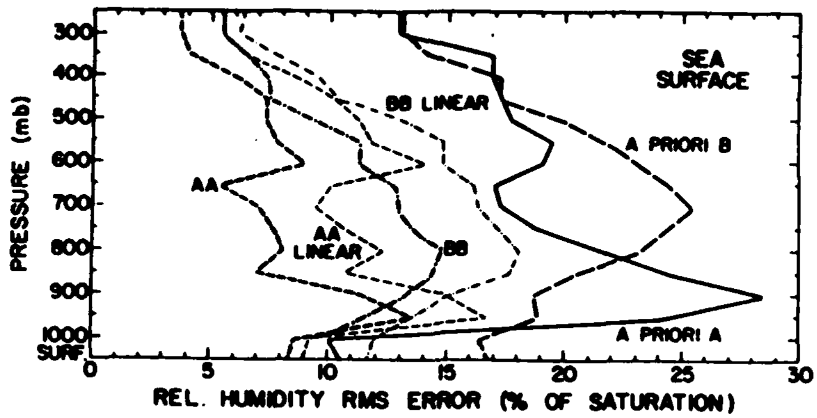

Figure 2-5 Residual errors in relative humidity profile over a smooth ocean surface. A priori A and B are variance of the sets used. Other curves such as AA, etc. denote retrievals from A set simulated data using A set statistics, etc.

Data was obtained over land (portions of Montana and North Dakota) during nine flights in May- June 1981. The retrieval assumed an initial relative humidity profile of 50% at each of the three selected fixed retrieval levels. It was noted that the resultant water vapor retrievals were not sensitive to the selected fixed levels. Surface temperature was assumed known and the temperature profile was obtained from nearby radiosonde data. Surface emissivities required in the iteration of the radiative transfer equation are obtained from the 92 GHz channel brightness temperature data. Using the assumed surface temperature and the temperature profile, the radiative transfer equation is solved for the surface reflectivity. It is remarked that about thirty iterations are required to obtain the demonstrated relative humidity profiles. Figure 2-6 from Wang et al., (1983) illustrates one of the retrievals obtained over land.

The authors remark that the retrievals agree quite well with the radiosonde humidity profiles. It is noted, however, that the retrieved humidities below about 4 km are strongly dependent on the assumed surface temperatures.

An uncertainty in the surface temperature of 5 K could result in 30% difference in the retrieved humidities. Over land this suggests that an accurate simultaneous surface temperature is also necessary. Note that this sensitivity to surface temperature was not observed for a profile retrieval over a lake water surface. Comparable humidity profiles were obtained with a 10 K difference in the assumed surface temperature. Errors in the temperature profile are also important. In a sensitivity test of temperature profile errors it was found that 1 and 5 K errors in the temperature resulted in about 10 and 50% errors, respectively, in the reference height relative humidities. Clearly, there is a need for an accurate temperature profile in this type of retrieval.

Over the water surface, however, there was a difference in the results obtained depending on whether the 92 GHz channel was used in the retrieval. Fundamentally, there was a 6 K difference between the simulated and observed brightness temperatures for this channel which the authors attribute to a possible uncertainty in the absorption coefficient at 92 GHz. (The absorption in this region is due primarily to the water vapor rotational continuum.)

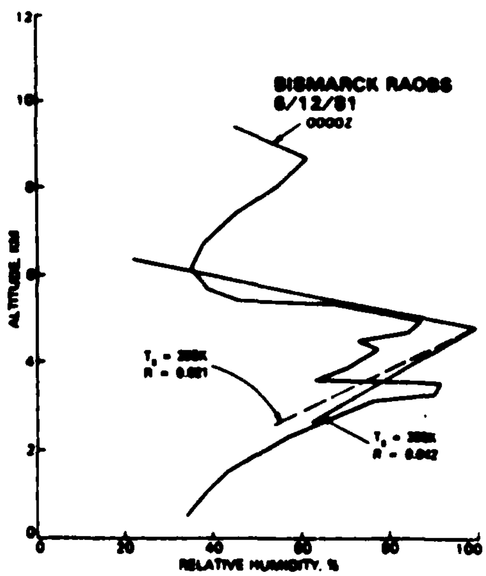

Figure 2-6 Relative humidity retrieval with CCOPE aircraft radiometer data obtained over land (Fig. 8, Wang et al, 1983).

Finally, the authors briefly discuss the effect of clouds. It is suggested that failure to account for the effect of clouds in the retrieval will result in an overestimate of the atmospheric water vapor immediately above and below the cloud cover.

2.5 Kakar, 1983

This work was carried out at the Jet Propulsion Laboratory (JPL) to investigate the accuracy of water vapor profiles achievable from the five channels selected for the Advanced Microwave Sounding Unit (AMSU) moisture package (designated AMSU-B). These channels include three in the vicinity of the water vapor resonance (183 +/-1,+/-3,+/-7 GHz) and two in window regions (90 and 150 GHz). Kakar used a Chahine (1972) type iterative retrieval supported by a well conceived radiative transfer model to perform the forward calculations. Details of the iterative scheme and convergence criteria are discussed in the paper. Temperature profiles were assumed known to within 2 K (achievable from state-of-the-art temperature sounders), and sensor noise levels were taken from the AMSU-B specifications. The sensitivity of the retrieval results to errors in the temperature profiles, variations in sensor noise, and different surface emissivities was also investigated. Figure 2-7 illustrates examples of four retrievals using noise of 1 K, a 2 K Gaussian error in the temperature profile and a surface emissivity of 0.7, corresponding to the ocean surface.

Retrieval accuracy statistics were calculated by performing numerical simulations for a set of fifty, randomly selected radiosonde soundings covering the latitude region from 30 S to 30 N. Two metrics were evaluated: (a) percent goodness-of-fit and (b) root-mean-square percent error between the retrieved and actual humidity profiles. Two values of surface emissivity, 0.7 and 1.0, were used for simulating oceanic and land retrievals, respectively. Approximately eight iterations were required for convergence and the retrieved profiles were smoothed using the sum of two exponentials to interpolate between retrieved levels.

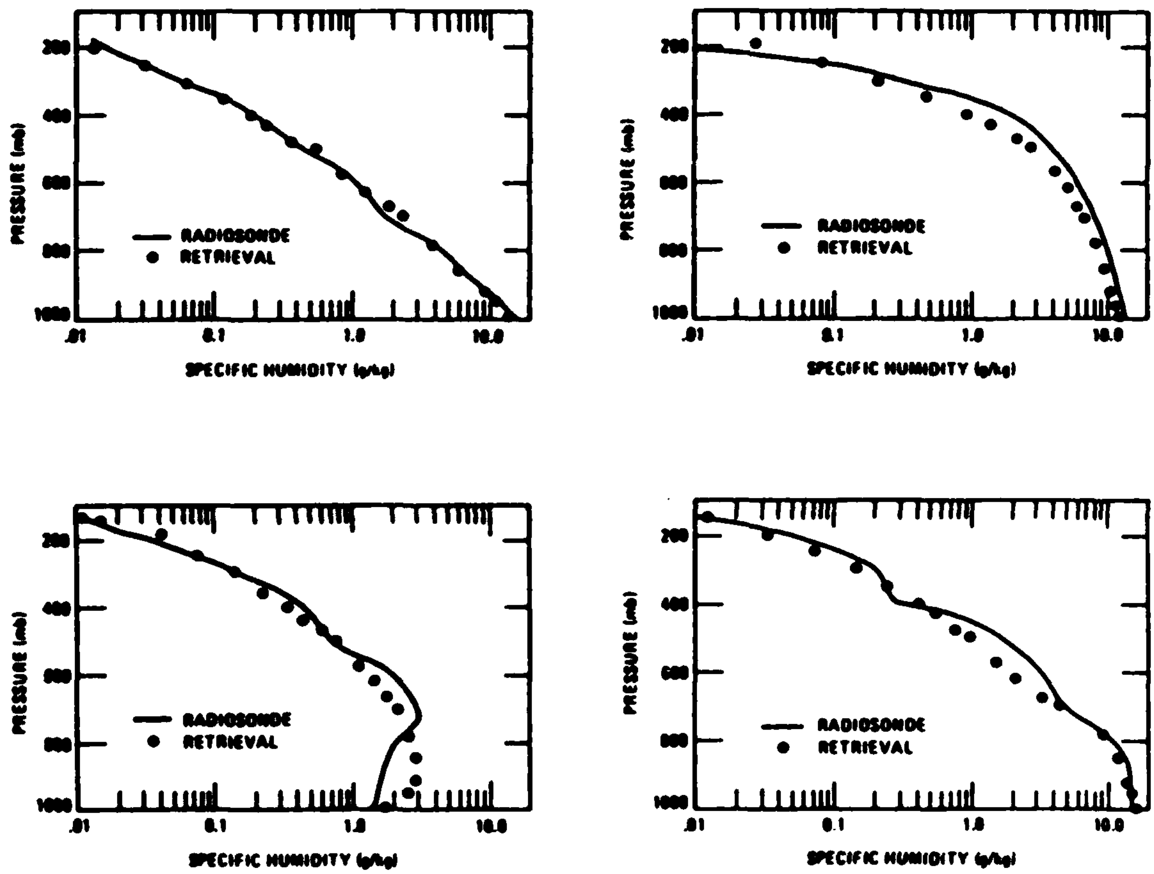

Figure 2-7. Simulated moisture profile retrievals from the AMSU-B (Kakar, 1983, Figure 1)

Kakar's results indicate the following:

(1) Retrieval accuracy is sensitive to errors in the temperature profile. In the middle troposphere, the percent goodness-of-fit decreases from 5-15% for an increase in temperature profile error from 0 K to 2 K.

(2) There is also a slight sensitivity of retrieval accuracy to sensor noise. The decrease in percent goodness-of-fit when sensor noise increases from 0 K to 2 K is about 10% throughout the humidity profile.

(3) Uncertainty in the surface emissivity also affects humidity profile retrieval accuracy. RMS% values increase by about 10% when the surface emissivity is unknown by +/- 0.05.

(4) Retrievals over land (simulated using emissivity 1.0), are less accurate than those over the ocean. This is due to the lack of contrast of water vapor emission against the more emissive land background. In the lower troposphere (700-100 mb), RMS% errors of about 20% for the ocean retrievals degrade to about 45% for those obtained over land.

2.6 Kakar and Lambrigsten, 1984

Here the authors of the previous study examined the feasibility of applying a statistical retrieval approach. The method is similar to that used by Gaut et al., 1975 and Rosenkranz et al., 1982. It differs, however, in one critical aspect. Here, rather than using all available channels in the development of the a priori statistics, the approach chooses an optimum subset of the available brightness temperature data at each pressure level at which moisture is to be estimated. (Here mixing ratio, rather than relative humidity, was used.) Results were compared to those obtained using the iterative scheme described in the previous section. Notably, the statistical correlation method used about two orders of magnitude less computer time.

The method is based on application of a simple linear regression where the amount of water vapor q(p) at pressure level p is expressed by the sum:

$$q(p) = a(p) + \sum_{i=1}^{N} b_i\ (p)\ T_b(\nu_i) \tag{2.5}$$

where a and b are regression coefficients and the T_b are the measured brightness temperatures. Regression coefficients were obtained from a data base consisting of soundings and corresponding channel brightness temperatures. An optimum subset was selected from along the N channels using the "leaps and bounds" procedure described by Pandey and Kakar (1983).

The procedure eliminated eight of the 20 AMSU channels (i.e., temperature and moisture sensing channels). From the remaining twelve, a few were selected for the estimation of water vapor at each of 15 pressure levels between 1000 and 300 mb. Channels selected for the tropics are shown in Table 2-3 along with the corresponding AMSU brightness temperature sensitivity. It is interesting to note that the 183+/-1 GHz channel was selected as a primary channel only for the 300 mb level, while the 183+/-7 GHz was selected for only the 570 and 950 mb levels. For these levels, nearly equivalent channels are also available. Thus, for the tropical retrievals, it is questionable whether these channels are needed.

Retrieval results, expressed as RMS absolute deviations averaged over an ensemble of 50 radiosondes are shown in Table 2-4. These results provide the standard deviation of the radiosonde set itself, and retrieval results for the statistical correlation approach over ocean and land and two forms of the iterative technique described in Section 2.5. Statistical results over the ocean are better than those over land as was the case using the iterative scheme. Notably, the statistical correlation results do not differ markedly from those of the iterative approach. In fact, they are somewhat better. The authors do note, however, that the iterative result was better in general when the a priori statistics were not representative of either the mixing ratio or temperature profile for the case examined.

Table 2-3 Optimum AMSU channels for the retrieval of water vapor as selected by the statistical correlation method. (Kakar and Lambrigsten, 1983; Table 2)

Pressure level (mb)	AMSU channels (GHz) 18.7	23.8	31.4	50.3	52.8	53.3	54.4	89.0	150.0	183.3 ± 1	183.3 ± 3	183.3 ± 7
300							•+			•	+	
350							•				•	
400							•				•	
430							•				•	
475						•					•	
500						•					•	
570	+	+	+		•			+				•
620	•	•						•				
670		•		•					•			
700	•	•							•			
780	•	•										
850			•					•	•			
920			•					•				
950	+	+	•+					+	•+			•
1000	•	•	•					•				
ΔT(K)	-0.5	0.5	0.5	0.4	0.25	0.25	0.25	1.0	1.0	1.0	1.0	1.2

Table 2-4 Comparison of simulated statistical and iterative retrievals. (Kakar and Lambrigsten, 1983; Table 3)

	50 Radiosondes		rms absolute deviation for 50 retrievals ($g\ kg^{-1}$)			
Pressure level (mb)	Average humidity ($g\ kg^{-1}$)	Standard deviation ($g\ kg^{-1}$)	Twelve channel statistical	Four channel iterative	Improved four channel iterative	Statistical over land
300	0.090	0.066	0.05	0.05	0.04	0.04
350	0.292	0.233	0.12	0.13	0.14	0.12
400	0.476	0.429	0.25	0.23	0.24	0.25
430	0.702	0.562	0.26	0.28	0.29	0.27
475	1.013	0.788	0.35	0.42	0.42	0.38
500	1.173	0.913	0.41	0.55	0.48	0.45
570	2.127	1.293	0.42	0.76	0.69	0.47
620	2.740	1.620	0.77	0.87	0.74	0.66
670	3.340	1.947	0.66	1.02	0.86	0.93
700	3.624	2.138	0.70	1.14	1.03	1.12
780	6.142	2.315	0.56	1.20	0.81	1.26
850	8.143	2.745	0.87	1.34	1.14	1.60
920	10.471	3.077	0.68	1.27	0.95	1.86
950	11.616	3.329	0.84	1.51	1.08	2.11
1000	13.447	3.859	1.40	2.33	1.56	2.54

2.7 Isaacs et al., 1985

Studies by Isaacs et al. (1985) and Isaacs and Deblonde (1985, 1987) have investigated two additional aspects of the 183 GHz retrieval problem: the effect of clouds and variable surface emissivity on water vapor retrieval accuracy. In the cited studies, a millimeter wave simulation model based on the AFGL RADTRAN code (Falcone et al., 1982) was used to parametrically vary atmospheric and surface background properties. Water vapor profile retrievals were obtained using a statistical retrieval method (see Equation 2.4) similar to that described by Gaut et al. (1975) and Rosenkranz et al. (1983). Channel frequencies were selected from both the SSM/T-2 and AMSU-B packages. Sensor noise was simulated by adding to the simulated brightness temperatures a Gaussian random signal with zero mean and standard deviation equal to the chosen noise level.

To simulate the effect of cloud within the field-of-view of the sensor, a set of cloud macrophysics models based on those used in the AFGL FASCODE model (Falcone et al., 1979) were incorporated within the simulation. The layer attenuation for each of five selected cloud types was calculated as a function of the model cloud's liquid water content and its model vertical extent. Cloud model type was randomly selected assuming that all cloud types were equally probable. Additionally, an option was provided to select a clear sounding. This latter option was incorporated so that the cloud effect was not overestimated. Furthermore, it was assumed that all clouds completely filled the field-of-view and that only a single cloud layer was present. Table 2-5 lists the cloud types used and their properties.

Table 2-5

Cloud Type Characteristics

Type	Liquid Water Content (gm^{-3})	Vertical Extent (km)
1. Stratus	0.15	0.5 - 2.0
2. Cumulus	1.00	1.0 - 3.5
3. Altostratus	0.40	2.5 - 3.0
4. Stratocumulus	0.55	0.5 - 1.0
5. Nimbostratus	0.61	0.5 - 2.5

Figure 2-8 illustrates the effect of cloud on the weighting functions for a typical oceanic sounding for three of the channel frequencies considered (90, 150, 183+/-7 GHz) both with and without an altostratus cloud in the field-of-view. The figure illustrates that the cloud seriously restricts the sensor's ability to sound the atmosphere by constraining brightness temperature contributions to levels in the vicinity of the cloud alone.

The effect of this cloud on simulated brightness temperature is shown in Figure 2-9a and b over ocean and land backgrounds, respectively. Here brightness temperatures for the SSM/T-2 are plotted as functions of the assumed liquid water content of the altostratus cloud. The solid horizontal line indicates the model cloud top temperature. The channels in the vicinity of 183 GHz generally peak too high in the atmosphere to see this cloud. Some effect on the 183+/-7 GHz channel can be seen. The "window" channels at 91.66 and for low liquid water content, at 150 GHz, however, are measurably affected. It can be seen that over the ocean, the cloud produces a warming effect since it is radiometrically warmer than the relatively low emissivity ocean surface. Over land, on the contrary, the cloud produces a cooling as it obscures the warmer surface, much as the case in the infrared.

Cloud effect on water vapor profile retrieval accuracy from the SSM/T-2 channel set is illustrated in Figure 2-10a and b over ocean and land, respectively. Plotted are layer RMS fractional error obtained as a function of clear and cloudy tropical oceanic soundings. It can be seen that useful retrievals should be provided in clear situations over the ocean, particularly in the middle troposphere. Over land, the retrievals are still good, although the improvement over the a priori climatology is not as dramatic. The enhanced retrieval skill over the low emissivity oceanic background can be extrapolated to characterize low emissivity surface types over land such as dry snow which can provide high contrast for atmospheric emission. The fractional RMS error over both backgrounds is increased considerably due to the presence of beam-filling cloud. The impact is particularly noticeable over the oceans where the clear retrievals are quite good.

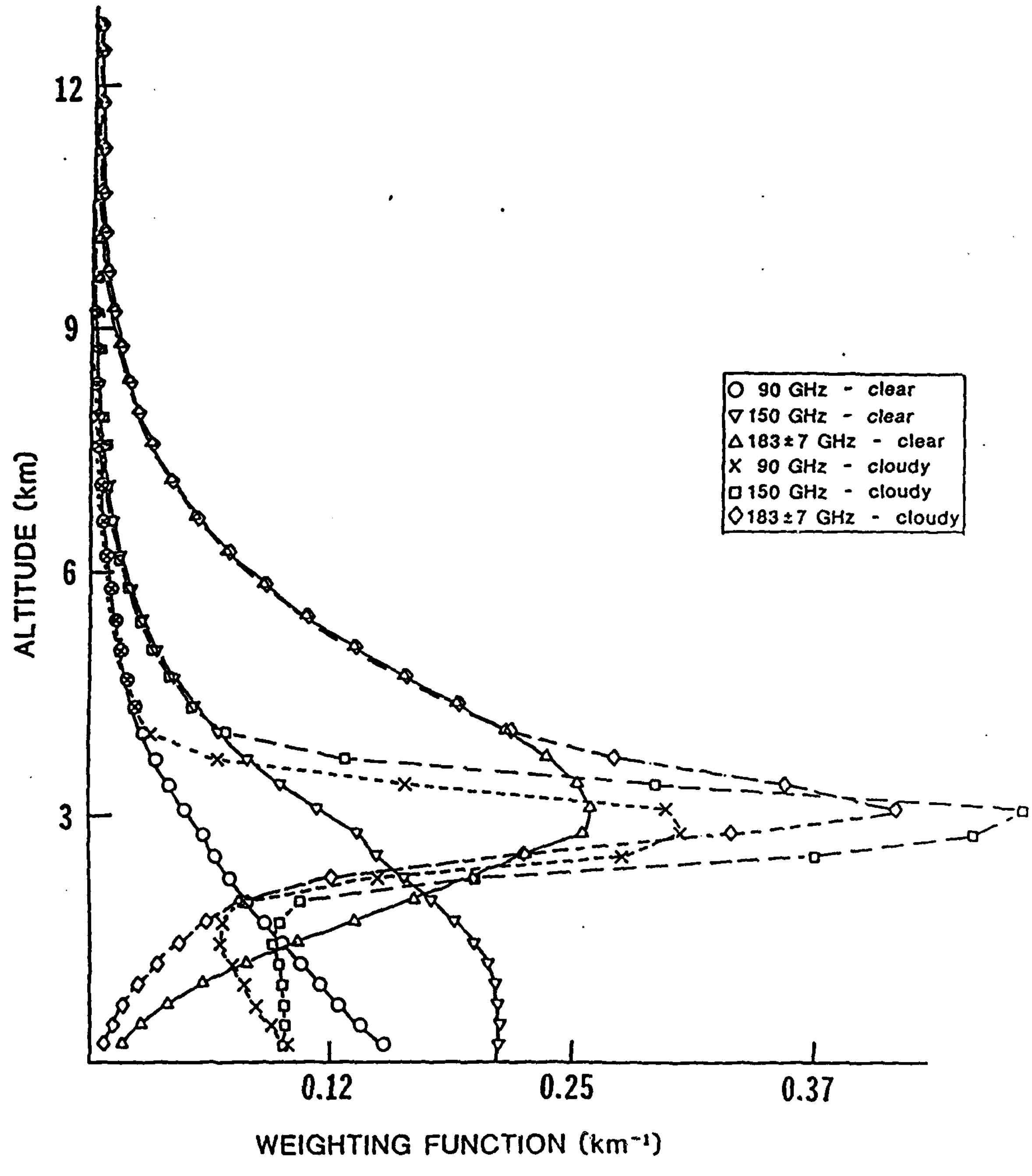

Figure 2-8 Millimeter wave weighting functions for tropical oceanic sounding at frequencies of 90, 150 and 183 ± 7 GHz: (a) clear atmosphere (solid) (b) altostratus cloud between 2.5 and 3.0 km (dashed).

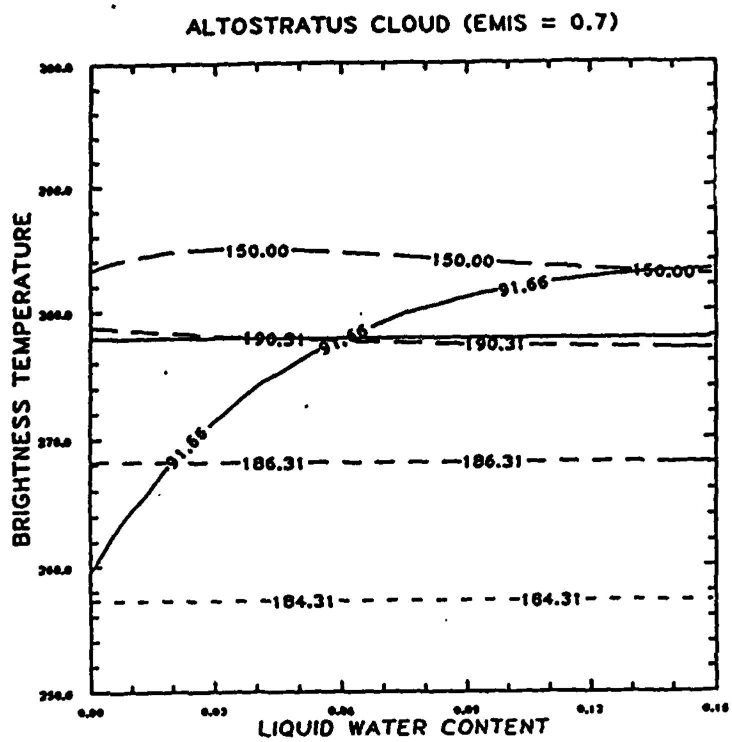

Figure 2-9a Brightness temperature at 90, 150, and 183 ± 1, ± 3, ± 7 GHz as a function of cloud liquid water content for an altostratus cloud over the ocean.

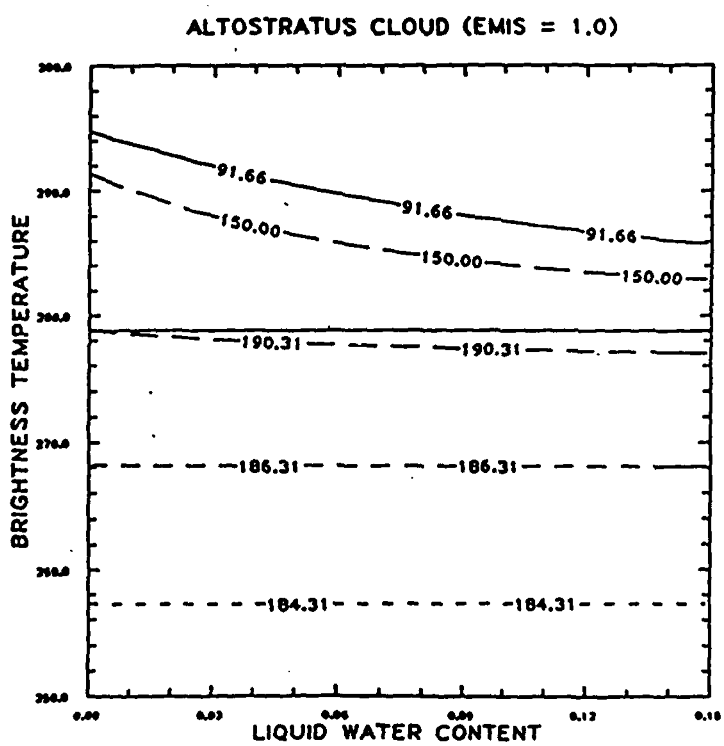

Figure 2-9b Brightness temperature at 90, 150, and 183 ± 1, ± 3, ± 7 GHz as a function of cloud liquid water content for an altostratus cloud over land.

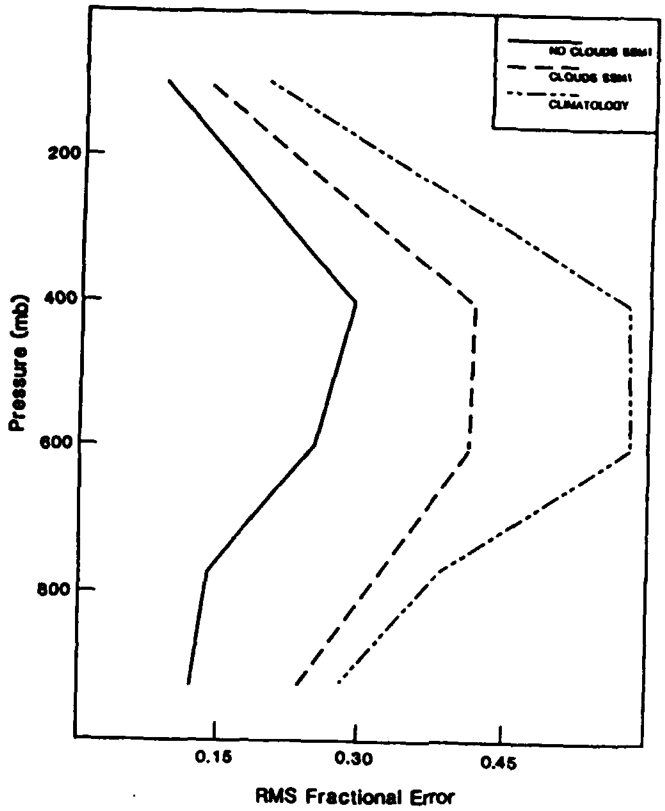

Figure 2-10a Water vapor retreival RMS fractional errors for tropical, oceanic soundings: (a) clear atmospheres (solid), (b) cloudy atmospheres (dashed), (c) climatology (short dashes).

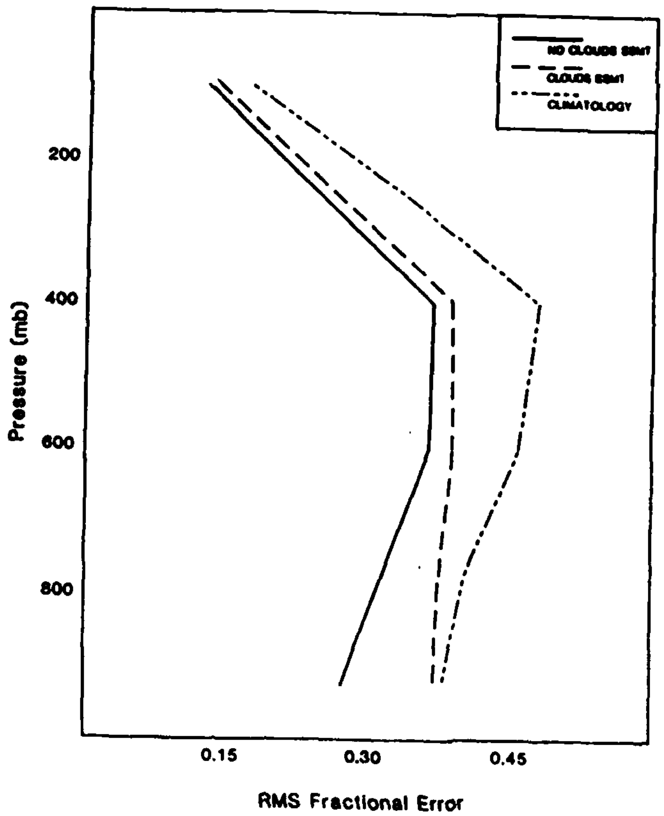

Figure 2-10b Water vapor retrieval RMS fractional errors for tropical land soundings: (a) clear atmospheres (solid), (b) cloudy atmospheres (dashed), (c) climatology (short dashes).

3. Summary of Results

Each of the studies described in the previous section has contributed to our overall understanding of the potential capability of 183 GHz radiometers to provide vertical water vapor profile retrievals. A number of recurrent themes emerge from this body of work concerning the dependence of profile retrieval accuracy on various considerations. For convenience, we have divided these themes into three categories including: (a) meteorological factors, (b) sensor system factors, and (c) retrieval approach considerations. These are summarized in this section.

3.1 Meteorological Factors

The radiative transfer equation provides insight into the dependence of measured millimeter wave brightness temperatures on various meteorological factors determined by the ambient atmosphere. These include: (a) the surface temperature, (b) the surface emissivity, (c) the temperature profile, and finally, (d) the moisture profile. The brightness temperature at frequency, ν, will be given by:

$$T_b(\nu)=\{\varepsilon_s T_s+(1-\varepsilon_s)[T_c\tau_\nu'(0)+\int_0^{p_s}T(p)d\tau_\nu']\}\tau_\nu(p_s)+\int_{p_s}^{0}T(p)d\tau_\nu$$

where

$$\tau_\nu(p) = \exp\left[-\int_0^{p}k(\nu,p')dp'/\mu\right]$$

and

$$\tau_\nu'(p) = \exp\left[-\int_p^{p_s}k(\nu,p')dp'/\mu\right]$$

The first term includes emission from the earth's surface and the reflection of downwelling atmospheric emission by the surface. The second term is the atmospheric emission itself. Atmospheric emission depends on both the temperature and water vapor profiles since they determine the local Planck function and the vertical distribution of path transmission through the absorption coefficient of water vapor.

Note that the surface emission/reflection term (i.e. the first term) has the transmittance from surface to space as a factor. Thus, surface temperature and emissivity contributions to brightness temperature are controlled by the atmospheric transmission properties. For frequencies where the atmospheric transmission to the surface is small (as it is in the vicinity of the 183.31 water vapor resonance), these contributions are of little consequence. Choice of such frequencies thus masks surface emissivity or temperature variations (cf. Gaut et al., 1975). Unfortunately, information on water vapor emission near the surface is also not obtainable. At lower frequencies where the atmosphere is more transparent, surface emission/reflection can be the largest contribution to brightness temperature. Over land, brightness temperature changes due to variable surface emissivity can mask those from atmospheric emission due to water vapor variations.

Surface emissivity plays a key role in determining the accuracy of millimeter wave water vapor retrievals in two ways. As a first order effect, it has been noted by a number of investigators that as a class, retrievals over land surfaces are less accurate than those over the oceans. The key difference between land and ocean retrievals, of course, is that at millimeter wave frequencies, *calm sea surface emissivities* are much less than unity, while land emissivities approach that of a blackbody. Thus, moisture in the lower atmosphere over the ocean is seen in emission against a radiometrically cold surface. By comparison, there is very little contrast between water vapor emission near the earth's surface over land and that of the surface itself. These sensitivity differences can seen in Figures 2-1 and 2-2 from Schaerer and Wilheit (1979). The effect of the underlying surface is manifested in the retrievals as illustrated by the "no clouds" results shown in Figures 2-10a, b for ocean and land, respectively.

Within the class of oceanic retrievals, uncertainties in surface emissivity specification also contribute to inaccuracies in the retrieved water vapor profiles. Surface emissivities over the ocean are variable due to the effects of wind-wave interactions and to a lesser extent, to surface temperature variations themselves. Kakar (1983) calculated the effect of absolute uncertainties of 0.02 and 0.05 on the root-mean-square percent errors for his ensemble of moisture retrievals. Errors increased by about 2 to 10 percent, respectively, and were largest near the surface. Similar results are reported by Isaacs and Deblonde (1985). For many purposes (especially tactical applications), the water vapor retrieval accuracy near the surface is of primary interest.

Regardless of whether land or ocean surfaces provide the background for the millimeter wave observation, surface emission depends on the physical temperature of the surface. Wang et al. (1983) demonstrated that retrieved relative humidity values in the lower atmosphere are strongly affected by surface temperature determinations. Their results indicated that a change by as much as 5 K in surface temperature could result in as much as a 30% difference in the retrieved humidities below 4 km. Conversely, a retrieval over a water surface showed little sensitivity to surface temperature. This is consistent with Kakar's (1983) findings regarding sensitivity to errors in surface emissivity over the ocean. Wang et al. (1983) suggested that precision temperature measurements are required to retrieve water vapor in the lower atmosphere over land.

There is general agreement that water vapor profile accuracy is bounded by that of the concurrent temperature retrieval. Reasonable water vapor profiles (20% and 45% RMS averaged over an ensemble of profiles, over ocean and land, respectively) are obtained with the 2 K RMS temperature retrieval accuracies achievable from state-of-the-art sounders (Kakar, 1983). For an individual sounding, Wang et al (1983) found that 1 and 4 K temperature shifts in the relevant radiosonde sounding resulted in up to 10 and 50% errors, respectively, in the resultant relative humidities. This suggests that precision temperature profiles measurements are also required. It may be pointed out in this regard that both Rosenkranz et al. (1982) and Kakar and Lambrigsten (1984) demonstrated that sensor data contributing independent information on the temperature profile and water vapor emission are essential for a good water vapor profile retrieval.

3.2 Sensor System Factors

These studies have examined the dependence of water vapor retrieval accuracy on sensor radiometric noise and channel selection. Accuracies achievable with an aircraft radiometer are illustrated by Wang et al. (1983). However, they used radiosonde temperature profiles to run their retrievals. Kakar (1983) and Isaacs and Deblonde (1985) demonstrate the sensitivity to noise in the range from 0.0 to 2.0 K. As expected, retrieval error increases with sensor noise levels. The effect is not drastic, however. It may be expected that these simulation studies underestimate the overall effects of noise in an operational sensor since scene noise and potential biases are not treated.

Channel selection is a more interesting question. Kakar and Lambrigsten (1985) have shown by careful statistical analysis which candidate channel frequencies provide information on water vapor as a function of frequency. Their analysis (see Table 2-3) emphasizes the importance of "window" channel information at frequencies below the 60 GHz oxygen complex and in the region between 60 GHz and the water vapor line at 183 GHz along with relevant data from the 60 GHz region itself (i.e. providing temperature profile data). For tropical atmospheres there seemed little justification for including channels in the 183 GHz region. Isaacs and Deblonde (1985) obtained similar results using an eigensystem approach. In that analysis it was shown that addition of a channel at 90 GHz provided much more information for the water vapor retrieval than did the 183 GHz channels. Gaut et al. (1975) made similar channel trade-off suggestions. It should be emphasized that these conclusions may not be valid in mid-latitude atmospheres where the water vapor burden is smaller and vertical water vapor variations are characteristically different than those in the tropics. This is due to the shift in the weighting functions with altitude as water vapor burden varies. In midlatitudes, channels will peak lower in the atmosphere than in the tropics.

3.3 Retrieval Approach Considerations

The retrieval system for water vapor consists of both the sensor and the algorithm used to reduce its data to useful meteorological profiles. The studies reviewed in the previous section utilized a variety of specific retrieval approaches (see Table 2-1). In general these can be classified as based either on statistics or physical iterative schemes (cf. Isaacs et al., 1986). The primary focus of these studies, however, was the efficacy of millimeter wave moisture retrieval. Thus, little effort was devoted to trading off the advantages of various retrieval approaches. A notable exception is the set of companion studies by Kakar (1983) and Kakar and Lambrigsten (1984) which compared a Chahine-type physical retrieval and a statistical approach, respectively. Based on their conclusions, the greater computational efficiency of the statistical approach is undebatable. Additionally, in this controlled simulation experiment, accuracies achieved via the statistical route were superior to those using the iterative scheme. These accuracy results apply to the ensemble statistics, however, and average over the details of individual profile retrievals. It should be noted that the authors mention that the iterative method gave superior results when the water vapor or temperature profiles were outside the range of the test ensemble. This is a key point. It is necessary to consider the validity and representativeness of the acquired statistical data base in operational retrieval processing. Often the meteorologically interesting situations are outside the domain of the expected a priori climatology.

4. Unanswered Questions and Unresolved Issues

The reviewed literature is notable, not only for contributions to our understanding of millimeter wave moisture sounding capabilities, but also for questions raised and issues left unresolved. In this section, these aspects of the *state-of-the-art of 183 GHz moisture* profile retrievals are addressed. The following topics represent gaps in our understanding of the fundamental millimeter wave physics required to perform sensor simulation and retrieval studies and shortfalls in the state of technique development necessary to fully utilize the data once they are available from spaceborne sensors. Much of this discussion is based on the working group reports of the "Workshop on Moisture Profiling Using the 183 GHz Line" held at the Air Force Geophysics Laboratory in April of 1986 (Hardy, personal communication 1986). No priority is implied by the ordering of the issues raised.

4.1 Millimeter Wave Optical Properties

4.1.1 Surface Emissivities

As discussed in Section 3, much information on lower atmospheric water vapor abundance is available from the brightness temperatures measured at essentially window frequencies. It is important, therefore, to understand the optical properties of surface backgrounds at frequencies between 60 and 190 GHz. This capability is needed, not only to support an intelligent simulation modeling capability, but also to interpret retrieval results obtained over geophysically diverse surfaces. The retrieval results have noted the characteristic accuracies associated with two general surface background types: ocean and land.

Although there is a consensus that land surfaces are highly emissive and generally Lambertian for incidence angles greater than about 45 degrees, the characterization is complicated by the presence of water (both frozen and liquid) and vegetation in various forms. Theory suggests that emissivity is highly dependent on the volumetric moisture content of land surfaces. At millimeter wavelengths the effect is enhanced as surface skin depths are decreased. Given the expected variability of surface moisture this effect will be difficult if not impossible to characterize with a static data base. Similar considerations apply to snow, ice, and certain types of vegetation. Measurements indicate, for example, that dry snow acts as a scattering medium. Model results indicate that scattering lowers surface emissivity significantly to a degree dependent on the snow microphysical properties, moisture content, and depth. Analogous considerations indicate that emissivity of the effective background can vary significantly with vegetative cover. It is not clear whether this behavior is fully understood and ground based measurements are lacking particularly at the higher frequencies required.

It is often assumed that the emissive behavior of the ocean surface is understood. In light of the sensitivity, albeit small, of retrieval results to variations in emissivity this assumption should be reassessed. Our confidence in ocean surface models is based primarily on experience at frequencies below 60 GHz. At the higher frequencies other surface roughness mechanisms may become significant factors. For example, surface roughness has been modeled as Lambertian. This may break down at higher frequencies. The role of sea foam also needs to be reinvestigated at higher wind speeds.

Finally, there is the spatial inhomogeneity of the field-of-view. For the SSM/T-2, the footprint will be on the order of 50 km. A considerable variation of surface type within the field-of-view be expected. It is not known to what extent the noise in the emissivity degrades the retrieved profiles even assuming that the mean emissivity is known.

4.1.2 Atmospheric Gaseous Absorption

The atmospheric transmission spectrum in the frequency range between 60 and 200 GHz is dominated by resonant absorption features of molecules such as oxygen, water vapor, and ozone, and by an absorption continuum. Simulation modeling in support of retrieval assessments requires an accurate rendition of these features.

Resonant absorption features are modeled by specifying a line shape and the necessary supporting absorption line parameters. The desired molecular absorption coefficient is obtained from the line shape function and relevant molecular abundances using the relationship:

$$\exp \frac{\sec\theta}{g} \sum_n \int_p^o k_n[\nu,p',T(p')]q_n(p')dp' \quad d\nu$$

Tabulations of required absorption line parameters are available from AFGL and JPL (Rothman et al., 1983; Poynter and Pickett, 1980). Uncertainties in the specification of the appropriate line shape and parameters can have a significant impact on the accuracy of sensor channel brightness temperatures used in the evaluation of a priori statistics for "D" matrix retrievals and in the efficacy of physical retrieval approaches. Wang et al. (1983), for example, note that 20% changes in the calculated water vapor absorption coefficients account for 1.0-1.6 K variations in the resultant brightness temperatures. Absorption line parameters, especially half widths, and, to a lesser extent, line shapes may have considerable uncertainty. Some simulation modelers have chosen to ignore these compilations and have relied instead on empirically tuned atmospheric transmission models.

Treatment of the continuum in this region has been historically controversial. The classical approach is that of Gaut and Reifenstein (1971) based on fitting experimental data. More recent improvements have been discussed by Clough et al. (1980) and Liebe (1980). The work done by LLewellyn-Jones at the Rutherford-Appleton Laboratories in the UK is notable in this regard (LLewellyn-Jones and Knight, 1981). Accurate modeling of the continuum is important to the water vapor problem, especially in light of the significance of information from the window channels at 90 and 150 GHz to retrieval accuracy as discussed in Section 2. The continuum is the dominant mechanism determining atmospheric transmission at these frequencies.

The collected knowledge concerning millimeter wave optical properties has been incorporated into a number of atmospheric transmission models. Among these, three have been widely applied. They are: (1) the Air Force Geophysics Laboratory RADTRAN (Falcone et al., 1982), the Air Force Geophysics Laboratory FASCODE (Clough et al, 1981), and (3) the Institute for Telecommmunication Sciences millimeter wave propagation model (MPM) (Liebe, 1985).

4.1.3 Dielectric Properties of Liquid Water and Ice

It is essential to understand the optical properties of clouds and hydrometeors on the frequency range from 60 to 200 GHz in order to evaluate their effect on water vapor profile retrievals. Conversely, given a sufficiently detailed understanding of these properties it may be possible to utilize brightness temperature data from this spectral region to infer useful meteorological properties of the clouds and hydrometeors themselves, especially when the data would otherwise be less than optimal for moisture retrieval purposes. Expressions currently used for the evaluation of the dielectric properties of liquid water (e.g. the complex index of refraction) are derived primarily from data obtained at frequencies below about 50 GHz and in the temperature range between 0 and 40 degrees C. For meteorological purposes it would be advantageous to obtain measurements of these properties at higher frequencies throughout the millimeter wave region and at temperatures below 0 degrees C. Lower temperatures are necessary to help characterize the properties of super-cooled water clouds.

The optical properties of ice are also of interest. There is general agreement in the real part of the complex index of refraction of ice. It has very little temperature and virtually no frequency dependence in the domain of frequencies and temperatures of geophysical interest. There appears to be considerable scatter, however, in the temperature and frequency dependence of the imaginary part of the complex index of refraction of ice (i.e. its absorption component) as measured by various investigators. Thus, the behavior of ice at millimeter wave frequencies is somewhat uncertain.

4.2 The Effects of Clouds and Precipitation

Virtually all of the research papers reviewed in Section 2 mention the need to quantify the potential effects of cloud on the retrieval of moisture profiles from millimeter wave brightness temperature data. Wang et al. (1983) gave mention to some data obtained over land in the presence of cloud and noted that brightness temperatures decreased. Virtually all of the other studies focused on simulations involving clear situations. Exceptions are the simulations done by Aerojet (see Appendix A) and those described by Isaacs et al. (1985) and Isaacs and Deblonde (1985). These studies suggest that cloud presence within the field-of-view can degrade the accuracy of profile retrievals (see Section 2.7).

A considerable number of assumptions were applied in performing these simulations, however, with respect to both the cloud optical properties and the typical spatial distribution of clouds. For example, it was assumed that clouds were beam-filling. The validity of this assumption is strongly dependent on the type of cloud treated and the size of the field-of-view. For typical clouds and the beam size specified in Appendix A for the SSM/T-2 partial cloudiness is more likely. Thus the cited results represent a worse case scenario. Additionally, single layer cloud systems were assumed. Realistically, one can expect a diversity of multiple layer clouds with spatial structure subresolution to the SSM/T-2 sensor. Other simulation problems include the specification of typical cloud top and base altitudes and the temperature and moisture profiles within the cloud. One of the problems with treating cloud in simulation is that upper air observations do not specifiy these cloud structure details, nor do they identify cloud type. Corresponding station data cannot be relied upon to characterize the atmosphere where the sounding was actually made. This modeling dilemma might be solved by obtaining some good quality aircraft and ground based radiometric data supported by a collateral simulation modeling effort.

These considerations apply not only to liquid water clouds, but to glaciated clouds as well. There is observational evidence to suggest that the role of ice clouds as attenuators of millimeter wave radiation may have been underestimated in the past (T. T. Wilheit, personal communication). This discrepancy may be due to complexes of ice crystals much larger than typical cirrus particles. Again radiometric studies will be necessary to quantify the magnitude and extent of the effect.

Finally, it should be noted that rain in the field-of-view will drastically change the observed brightness temperatures. Thus, flagging rain contaminated cells will be just as important in the algorithms for millimeter wave moisture retrieval as it is in those for microwave temperature retrieval, perhaps more so. In one sense, rain is much easier to detect at these higher frequencies (see Isaacs et al., 1985). The problem will be, as it is in the case of the SSM/T, to determine when precipitating cells cover only a portion of the field-of-view. In these cases, the correlation of the observed brightness temperatures with expected moisture is altered from that obtained in the non-precipitating case, and the accuracy of the retrieved moisture is questionable. Higher resolution data either from the microwave imager (SSM/I) or visible and infrared sensors can provide beneficial supplementary data in such cases. These multisensor applications should be explored.

4.3 Surface Elevation Effects

Much of the earth's surface is not at sea level. Brightness temperature simulations, whether used to evaluate the covariance relationships for "D" matrix statistics or as part of a physical retrieval scheme, begin integrating atmospheric emission from a reference level, usually the surface or 1000 mb. When treating the temperature retrieval problem, the effect of elevation within a beam can be handled by subtracting the emission (and attenuation of reflected radiation) from that portion of the atmosphere "below" the physical surface from the simulation. This is possible since the amount of emitting uniformly mixed gas "missing" from the atmosphere is related hydrostatically to the pressure difference between the standard surface and the elevation within the field-of-view. A variation of this approach is employed in the retrieval algorithm for the SSM/T.

Application of a similar approach for water vapor retrievals is problematical. There is no analogous simple connection between the amount of emitting water vapor at elevation and the mean surface pressure level within the beam. This problem is currently being worked on by the group at Aerojet (A. Stogryn, personal communication).

5. Conclusions

The feasibility of retrieving atmospheric vertical moisture profiles from millimeter wave brightness temperature data has been demonstrated by the studies reviewed in this report. This has been accomplished using both actual data from an aircraft borne sensor system and in simulation. These studies suggest that water vapor abundances in the lower troposphere will be measurable over the oceans in calm seas to an accuracy of up to 20%. Over higher emissivity land surfaces, the contrast advantage of water vapor emission against the radiometrically cold ocean background will be lost and accuracies will degrade to about 40%. In addition to this gross dependence on the type of background viewed, retrieval accuracies will depend on the precision of the coincident retrieved temperature profile, surface temperature, and surface emissivity. The characteristics of the sensor system are also factors. Channel selection is the most critical factor. Channel sensitivity and noise are also considerations. The studies reviewed have generally used consistent channel sets and similar noise equivalent brightness temperature values based on current sensor technology.

It should be noted that simulation studies generally result in optimistic predictions of sensor performance. In simulation studies, sensor channel brightness temperatures are calculated using deterministic radiative transfer models based on our current understanding of state-of-the-art atmospheric and surface background optical properties. Since our current understanding is somewhat incomplete, the results of these models must be viewed in proper perspective. Some of the uncertainties noted in the discussions in Section 4 include those related to background properties, atmospheric gaseous absorption, the optical properties of liquid water and ice, and models of cloud and hydrometeors. In spite of these uncertainties simulation model results provide a powerful tool in the sensor design phase. Such studies have provided an opportunity to investigate the accuracy of the retrieved profiles parametrically with varied, realistic meteorological conditions using a number of potential candidate sensor system concepts.

A considerable number of questions remain unanswered. One of the most important of these is the utility of the data to be collected from the proposed millimeter wave moisture sounder (the SSM/T-2) to satisfy the requirements of Air Force applications models. The application of moisture profile data to the numerical weather prediction capability at the Air Force Global Weather Central is the focus of the observing system simulation experiment to be carried out as part of the current research program at AER.

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Appendix A - The SSM/T-2 Millimeter Wave Moisture Sounder

An enhancement of the current seven channel SSM/T microwave temperature sounder operating in the 60 GHz oxygen band (henceforth called the SSM/T-1), the SSM/T-2 millimeter wave moisture sounder will add an additional five channels of information, two in window regions and three in the vicinity of the 183.31 GHz water vapor line. The hardware package will be constrained to 30 lbs and 30 watts power consumption and generate a data rate increment of 324 BPS.

The instrument is designed for cross-track scanning with 28 beam positions in 3 degree steps within an 8 second scan period. The limits of the cross track scan are thus 40.5 degrees to each side of the subsatellite track. Scanning will be synchronous with the SSM/T-1. Pointing angle accuracy will be limited to a maximum of 0.4 degrees scan plane alignment, 0.4 degrees beam position repeatability, and 0.4 degrees actual beam position tolerance about the desired position (Aerojet ElectroSystems, 1983).

Major SSM/T-2 radiometric requirements are summarized in Table A-1.

Table A-1 Major Radiometric Requirements for the SSM/T-2 Millimeter Moisture Sounder (A. Stogryn, Aerojet, personal communication)

Chan No.	Center Freq. (GHz)	IF Bandwidth (GHz)	RF Pass bands (GHz)	Center Freq. Stability (MHz)	Radiometer Sensitivity (K)	Calibration Accuracy (K) Goal	Max
1	183.310 +/- 3.0	1.0	179.810-180.810/ 185.810-186.810	200	0.6	1.0	1.5
2	183.310 +/- 1.0	0.5	182.060-182.560/ 184.060-184.560	200	0.8	1.0	1.5
3	183.310 +/- 7.0	1.5	175.560-177.060/ 189.560-191.060	200	0.6	1.0	1.5
4	91.655 +/- 1.25	1.5	89.655-91.155/ 92.155-93.655	200	0.6	1.0	1.5
5	150.000 +/- 1.25	1.5	148.000-149.500/ 150.500-152.000	200	0.6	1.0	1.5

The spatial resolution of the water vapor profiles will be determined by the antenna beam specifications. Major antenna requirements are summarized in Table A-2.

Table A-2 SSM/T-2 Antenna Beam Requirements (A. Stogryn, Aerojet, personal communication)

Channel Number	Center Frequency (GHz)	Half-Power Beamwidth Mean Tol (Degrees)	Beam Efficiency (%)	Polarization (L or R)
1	183.31+/-3	3.0 0.3	>95	Unspecified
2	183.31+/-1	3.0 0.3	>95	Unspecified
3	183.31+/-7	3.0 0.3	>95	Unspecified
4	91.655+/-1.25	6.0 0.6	95 (Goal)	Unspecified
5	150.0+/-1.25	3.7 0.4	95 (Goal)	Unspecified

The channel polarizations have been left unspecified to permit simplification of the antenna and RF channel multiplexer. With the specified half-power beamwidths the field-of-view for each of the 183 GHz channels will be about 44 km while that for the 90 GHz channel will be about 87 km. The 150 GHz footprint will be slightly larger than the 183 GHz footprint. Given the cross-track scanning geometry, each SSM/T-1 temperature retrieval footprint will correspond to approximately sixteen SSM/T-2 183 GHz footprints. An example of the SSM/T-2 scanning pattern and its relation to the SSM/T-1 scanning pattern is illustrated in Figure A-1. This example was generated by a DMSP scan line generation program developed for this study. The program assumes a nominal DMSP sun synchronous circular orbit.

An assessment of the potential accuracy of the instrument was obtained by a simulation study performed by the instrument contractor. Simulated brightness temperature data sets were constructed for ensembles of radiosonde data both over land and the ocean and using clear and cloudy soundings. Table A-3 presents the results of this study based on a simple statistical regression of water vapor amounts in four layers with four of the channels given in Table A-1 (at the time the simulation was done a four channel instrument was considered; channel 4 was not included). There is a marginal improvement in retrieval accuracy throughout the profile when the additional channel at 91.655 GHz is included in the statistics (Isaacs and Deblonde, 1985).

Table A-3 Simulated DMSP SSM/T-2 RMS relative retrieval errors for vertical moisture profile over land and ocean with clear and cloudy fields of view. (Aerojet, briefing slide, 1983)

Parameter	Relative Retrieval Error over Ocean (%)		Relative Retrieval Error over Land (%)	
	Clear	Cloudy	Clear	Cloudy
Total Integrated Water Vapor	14.0	12.6	43.0	36.3
Integrated Water Vapor (SFC-850mb)	17.9	31.5	48.5	60.5
Integrated Water Vapor (850-700mb)	23.6	40.6	49.5	61.7
Integrated Water Vapor (700-500mb)	33.6	58.6	37.8	50.4
Integrated Water Vapor (500-0 mb)	29.4	40.1	36.5	45.0

END
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